# A Demonstration of Fat and Grease as an Industrial Boiler Fuel

**Principal Investigator:**
Dr. Thomas T. Adams, P.E., Public Service Associate
UGA Engineering Outreach Service (EOS)

**Coinvestigators:**
Jim Walsh, GA Tech EDI
Mike Brown, GA Tech EDI
Dr. John Goodrum, UGA Bio. & Ag. Eng.
Dr. Jackie Sellers, UGA Bio. & Ag. Eng.
Dr. Keshav Das, UGA Bio. & Ag. Eng.

**Project Administrator:**
Dr. E. Dale Threadgill, Director
Faculty of Engineering
The University of Georgia

**Project/Report Manager:**
Robert J. Synk, P.E., Project Management Resources, Inc.

**Project/Report Contributors:**
Erin Callaghan, Public Service Representative, UGA, EOS
Bryan Graffagnini, Research Engineer, UGA EOS
Javier Sayago, Chemist, UGA EOS

**The University of Georgia**
Engineering Outreach Service
Driftmier Engineering Center
Athens, GA 30606-4435

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Poultry Protein & Fat Council of the U.S. Poultry & Egg Association
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The University of Georgia

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## EXECUTIVE SUMMARY


The University of Georgia (UGA) Engineering Outreach Service (EOS) used fats and grease (chicken fat, yellow grease, choice white grease, and beef tallow) as industrial boiler fuels in the 100,000 lb./hr. No. 2 boiler at the UGA steam plant during January and February 2002. The project was funded by the Fats and Proteins Research Foundation, Inc. and the Poultry Protein & Fat Council of the U.S. Poultry & Egg Association. The objectives of the project were to publicly demonstrate the use of biofuel for industrial steam production and to examine the procedures necessary for its use.

**Combustion Test Program Summary**

| Fuel | No. of Tests |
|---|---|
| Natural Gas | 9 |
| Choice White Grease | 10 |
| Choice White Grease - Fuel Oil Blend | 12 |
| Tallow | 13 |
| Tallow Fuel - Oil Blend | 15 |
| Yellow Grease - Fuel Oil Blend | 19 |
| Yellow Grease | 21 |
| No. 2 Fuel Oil | 22 |
| Chicken Fat - Fuel Oil Blend | 23 |
| Chicken Fat | 29 |
| Total | 173 |

Tests were conducted Jan. 28 thru Mar. 15, 2002.

Biofuels, either singly or blended with No. 2 fuel oil, are technically and economically viable alternatives to No. 2 fuel oil. Biofuels are user friendly and less hazardous than petroleum fuels. The addition of biofuel combustion capability is simple and inexpensive. It is not necessary to replace or compromise the operation of existing fossil fuel systems.

Industrial boiler operators can use these results to economically justify the use of biofuels and to support air emissions permit submittals. Even lower emissions levels may be obtained from boilers employing advanced combustion systems.


**Summary of Results:**

1. Laboratory analyses showed that the fats and greases tested have high heating value, low ash, negligible sulfur, low moisture, and other physical and chemical properties conducive to their use as boiler fuel. Heating values for the biofuel blends tested are within 95% of the heating value of No. 2 fuel oil.

2. The 100,000 lb./hr. No. 2 boiler at the UGA steam plant was retrofitted to burn biofuels for approximately $31,000, including the cost to add flue gas recirculation (FGR). This amount does not include any expense for the construction of fuel storage facilities, which were not required for the demonstration program. The biofuel heat exchanger was obtained without cost to the project. It was not necessary to replace or modify the boiler fuel train or nozzle for these tests.

3. The tests demonstrated that the biofuels burn cleanly, readily, without odor and without damage to boiler equipment.

4. During this test program, biofuels produced steam within 3.8% to 5.3% of the efficiency of No. 2 fuel oil. Biofuels blended with No. 2 fuel oil were more efficient than unblended biofuels, and can actually produce steam with more efficiency than No. 2 fuel oil. Throughout the tests part load efficiency was greater than maximum load efficiency, and steam production with FGR was more efficient than without FGR.

5. Biofuels are clean burning. They generally produce fewer combustion emissions than No. 2 fuel oil.

6. Flue gas recirculation is an effective way to reduce $NO_x$ emissions for both fossil and biofuels.

**Impact of the Research Results relative to the requirements for Boiler No. 2 in the UGA Part 70 Operating (air emissions) Permit ("the Permit"):**

1. The Permit prohibits the burning of any fuel whose sulfur content exceeds 1.3% (para. 3.2.1). The maximum sulfur content of any biofuel tested was 0.007%, and 0.13% for any biofuel blended with No. 2 fuel.

2. The Permit limits particulate matter emissions to 0.417 lb/mmBtu (para. 3.4.1). The maximum total particulate (non-condensible and condensible) emission rate of any biofuel was 0.083 lb/mmBtu.

3. The Permit limits visible emissions to 40% opacity (para. 3.4.9). Smokestack opacity ranged between 0% and 11% during the biofuel tests.

**Impact of the Research Results relative to the GA Rules for Air Quality Control (the "Rules"):**

1. The Rules (Sections (2)(d)2 & 3) limit particulate emissions from all fuel-burning equipment, of any size, to 0.10 lb/mmBtu and opacity to 20%. The maximum total particulate (non-condensible and condensible) emission rate of any biofuel was 0.083 lb/mmBtu. Smokestack opacity ranged between 0% and 11% during the biofuel tests.

2. The Rules (Section (2)(d)4) limit $NO_x$ emissions to 0.3 lb/mmBtu from fuel oil burning equipment, of any size, in an attainment area. The maximum $NO_x$ emission rate of any biofuel tested was 0.23 lb/mmBtu.

**Contents**



**Acknowledgements**


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- UGA steam plant personnel, in particular: John Benca, Jim Olbrych, Danny Langston, Jerry Bray, Dwight Epps and Doug Pittard,
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- UGA faculty, in particular: Dr. John Goodrum, Dr. Jackie Sellers, and Dr. Keshav Das,
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- The Georgia Environmental Partnership.

# 1. INTRODUCTION

## 1.1. History and background, Engineering Outreach Service (EOS)

In 1994, responding to state initiatives to increase the rate of technology transfer out of the University System of Georgia laboratories and into the workplace, The University of Georgia began to offer Engineering Outreach and Public Service to increase the competitiveness of the state's industries. UGA has concentrated on providing to industries on-site services in the areas of research and development, technical and practical assistance, regulatory assistance, energy and water conservation, development of alternative energy, by-product recovery, pollution prevention, bioprocessing, value-added processing, and waste minimization/ treatment. These services are being delivered mainly to industries and to municipal and county governments. EOS offered to conduct combustion testing of rendered fats, oils, and grease when it learned of the pioneering work conducted by Roger Smith, Vice President Engineering Services, at American Proteins, Inc.

## *1.2.* Project Objectives for *A Demonstration of Chicken Fat as an Industrial Boiler Fuel:*

- Fuel Characterization: Samples of the fats and greases will be laboratory tested to analyze appropriate physical, chemical and combustion characteristics.

- Capital Cost Minimization: The test program will evaluate how to minimize the modifications and resulting capital expense required to convert an industrial boiler to alternative biofuel firing.

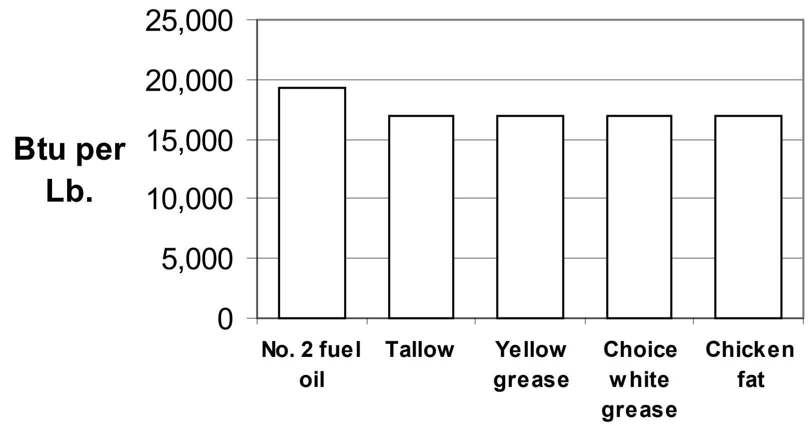
- Combustion Tests: Operating and emissions data will be obtained from an industrial boiler fueled with fats and greases, both singly and blended with No. 2 fuel oil.

- Publish results: Technology transfer publication.

## 1.3. Facts – Fats and Greases

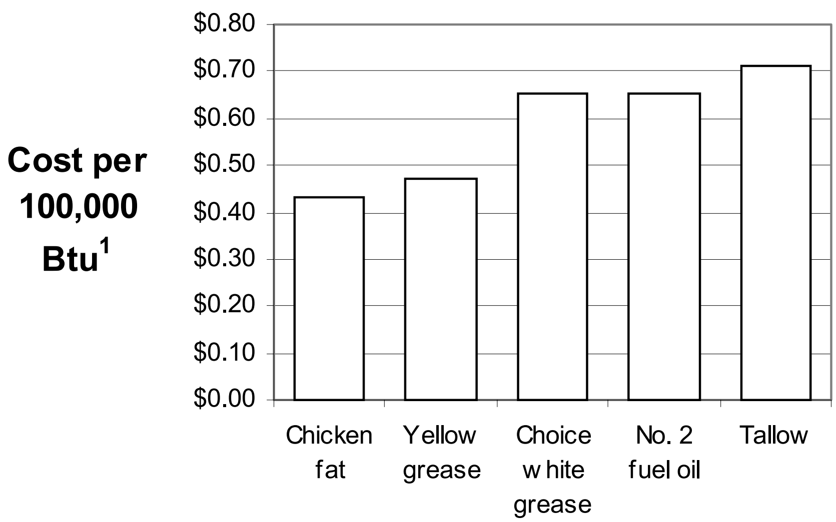
Readily available from meat, poultry and other food-processing operations, chicken fat, yellow grease, choice white grease, and beef tallow were purchased locally. They are competitively priced relative to No. 2 fuel oil, and can represent significant cost savings. The annual production of these biofuels in Georgia alone exceeds 100 million gallons (potentially, over 120 million therms of energy).

*Fig. 1.* **Fuel Energy Content**[1]




1) PSC Analytical Services, Reading, PA

*Fig. 2.* **Fuel Costs**[2]




1) Costs based upon delivered price to UGA June 2001 and Jan. 2002.
2) PSC Analytical Services, Reading, PA

## 2. ANALYSIS OF FATS AND GREASE

### 2.1. Introduction

Laboratory analyses of the fats and grease (biofuel oils) established their commercial specifications relative to standard market product designations. The physical properties of the biofuel oils were used to design the test facility at the UGA central steam plant.

### 2.2. Sampling Procedures

During the combustion test program, the test team randomly collected three 500-ml samples of each fuel, one each at the beginning, middle and end of each test series. A total of (33) fuel samples were obtained: six (6) samples each of chicken fat and yellow grease; and three (3) samples each of choice white grease, tallow, No. 2 fuel oil and the blends of chicken fat, yellow grease, choice white grease and tallow. (All blends consisted of 33% fat or grease and 67% No. 2 fuel oil.) The team also collected four (4) samples of various solid combustion by-product residues from inside the boiler.

The project procedures maintained sample chain of custody from initial sampling through analysis.

After initial cooling, the test samples were secured in refrigerated storage (4 deg. C.) while at UGA. The test samples were divided into smaller samples for analyses by the UGA laboratories and by commercial laboratories. The samples analyzed by commercial laboratories were overnight shipped in "cold packs".

*Fig. 3.* Fuel sampling during test

## 2.3. Fat and Grease Properties

***Table 1*, Fat and Grease Properties**[1]

| Test | Chicken Fat | Yellow Grease | Choice White Grease | Tallow |
|---|---|---|---|---|
| Fatty Acid Profile, % Relative: | | | | |
| C08:0 | <0.10% | <0.10% | <0.10% | <0.10% |
| C10:0 | <0.10% | <0.10% | <0.10% | <0.10% |
| C11:0 | <0.10% | <0.10% | <0.10% | <0.10% |
| C12:0 | <0.10% | <0.10% | <0.10% | <0.10% |
| C14:0 | 0.57% | 0.70% | 1.57% | 2.73% |
| C14:1 | 0.26% | 0.14% | 0.36% | 0.50% |
| C15:0 | <0.10% | 0.11% | 0.26% | 0.43% |
| C15:1 | <0.10% | <0.10% | <0.10% | 0.16% |
| C16:0 | 22.76% | 14.26% | 22.04% | 22.99% |
| C16.1 | 8.37% | 1.43% | 5.03% | 2.86% |
| C16.2 | <0.10% | <0.10% | <0.10% | <0.10% |
| C16.3 | <0.10% | <0.10% | <0.10% | <0.10% |
| C16.4 | <0.10% | <0.10% | <0.10% | <0.10% |
| C17:0 | 0.11% | 0.33% | 0.63% | 1.35% |
| C17:1 | 0.12% | 0.23% | 0.43% | 0.75% |
| C18.0 | 5.36% | 8.23% | 9.95% | 19.44% |
| C18.1 | 42.07% | 43.34% | 42.45% | 41.60% |
| C18.2 | 17.14% | 26.25% | 13.17% | 3.91% |
| C18.3 | 1.07% | 2.51% | 0.97% | 0.49% |
| C18.4 | 0.22% | 0.47% | 0.29% | 0.36% |
| C20.0 | <0.10% | 0.33% | 0.14% | 0.14% |
| C20.1 | 0.45% | 0.48% | 0.56% | 0.33% |
| C20.2 | 0.20% | <0.10% | 0.19% | <0.10% |
| C20.3 | 0.19% | <0.10% | 0.12% | <0.10% |
| C20.4 | 0.45% | <0.10% | 0.34% | <0.10% |
| C20.5 | <0.10% | <0.10% | 0.11% | <0.10% |
| C21:5 | <0.10% | <0.10% | <0.10% | <0.10% |
| C22:0 | <0.10% | 3.50% | <0.10% | <0.10% |
| C22:1 | <0.10% | <0.10% | <0.10% | <0.10% |
| C22:2 | <0.10% | <0.10% | <0.10% | <0.10% |
| C22:3 | <0.10% | <0.10% | <0.10% | <0.10% |
| C22:4 | 0.10% | <0.10% | <0.10% | <0.10% |
| C22:5 | <0.10% | <0.10% | 0.14% | <0.10% |
| C22:6 | <0.10% | <0.10% | 0.22% | <0.10% |
| C24:0 | <0.10% | 0.12% | <0.10% | <0.10% |
| C24:1 | <0.10% | <0.10% | <0.10% | <0.10% |
| unknown components | 0.56% | 0.72% | 1.03% | 1.96% |
| MIU Analysis: | | | | |
| Moisture & Volatiles | 0.12% | 0.38% | 0.24% | 0.17% |
| Insoluble Impurities | 0.08% | 0.06% | 0.29% | 0.12% |
| Unsaponifiable Matter | 0.51% | 0.42% | 0.73% | 0.30% |

1) Woodson-Tenent Laboratories, Memphis, TN

To establish the commercial specifications of the fats and greases relative to standard market product designations, Woodson-Tenent Laboratories Division of Eurofins Scientific, Inc., Memphis, TN performed a fatty acid analysis of one sample each of chicken fat, yellow grease, choice white grease and tallow, Table 1. The fatty acid profiles were determined using gas chromatography (AOCS method CE2-66/CE1-620, 0.01% accuracy).

In addition, Woodson-Tenent performed MIU (moisture, impurities, unsaponifiables) analyses of eight (8) biofuel samples, two (2) samples each of chicken fat, yellow grease, choice white grease and tallow, Table 1.

2.4. Viscosity and Specific Gravity

In the summer of 2001, the UGA Biological and Agricultural Engineering (BAE) Department analyzed representative samples of chicken fat and yellow grease, obtained from a local company, to establish a range of viscosity and specific gravity for the design of the test facility.

In the spring of 2002, BAE analyzed fuel samples collected during the test program. The UGA laboratory used a Brookfield LVT viscometer to determine dynamic viscosity (1% accuracy and 0.2% full-scale reproducibility). Specific gravity was measured directly. The dynamic viscosity of each fat and grease, of four (4) biofuel blends and of No. 2 fuel oil was measured over a range of five (5) temperatures and five (5) shear rates. The specific gravity of each fat and grease and of No. 2 fuel oil was measured over a range of five (5) temperatures. One sample of each fuel was tested. All biofuel blends consist of 33% biofuel and 67% No. 2 fuel oil. No. 6 fuel oil viscosity and specific gravity are given below for reference.

***Table 2*, Biofuel & Fuel Oil Physical Properties**

| Fuel | Dynamic Viscosity, cP | Specific Gravity |
|---|---|---|
| No. 2 Fuel Oil [1] | 2.3 [4, 5] | 0.83 [4] |
| Choice White Grease Blend [1] | 4.7 [4, 5] | not analyzed |
| Yellow Grease Blend [1] | 4.9 [4, 5] | not analyzed |
| Tallow Blend [1] | 5.2 [4, 5] | not analyzed |
| Chicken Fat Blend [1] | 12.6 [4, 5] | not analyzed |
| Chicken Fat [1] | 23.3 [4, 5] | 0.89 [4] |
| Yellow Grease [1] | 23.3 [4, 5] | 0.89 [4] |
| Tallow [1] | 24.2 [4, 5] | 0.89 [4] |
| Choice White Grease [1] | 25.0 [4, 5] | 0.88 [4] |
| No. 6 Fuel Oil [2] | 490 [3] | 0.97 [3] |

1) Goodrum et al., 2002; 2) Babcock & Wilcox, 1976; 3) data at 38 deg. C.; 4) data at 54.4 deg. C.; 5) data at 12.94 $s^{-1}$ shear rate

## 2.5. Ultimate Analysis and Heating Value

PSC Analytical Services, Reading, PA analyzed a total of (33) biofuel, biofuel/fuel oil blends and fuel oil samples to establish their comparative combustion chemistry and heating values. (All biofuel blends consist of 33% biofuel and 67% No. 2 fuel oil.) PSC used standard ASTM test methods for all analyses. PSC is certified/ accredited by the USEPA, NIOSH, the US Corp of Engineers, and (12) states.

***Table 3*, Fuel Energy Content and Ultimate Analysis** [1]

| Fuel | Energy Content, Btu/Lb. | Ash | Carbon | Hydrogen | Nitrogen | Oxygen | Sulfur | Moisture |
|---|---|---|---|---|---|---|---|---|
| Chicken Fat | 16,873 | 0.14% | 75.3% | 11.4% | 0.04% | 13.1% | 0.006% | (trace) |
| Chicken Fat - Fuel Oil Blend | 18,223 | 0.02% | 82.7% | 12.2% | 0.06% | 3.83% | 0.12% | (trace) |
| Yellow Grease | 16,899 | 0.02% | 76.4% | 11.6% | 0.03% | 12.1% | 0.005% | (trace) |
| Yellow Grease - F.O. Blend | 18,543 | 0.01% | 80.2% | 11.6% | 0.07% | 8.01% | 0.13% | (trace) |
| Choice White Grease | 16,893 | 0.08% | 76.5% | 11.5% | 0.05% | 11.6% | 0.007% | (trace) |
| Ch. Wht. Grease - F.O. Blend | 18,493 | 0.01% | 82.2% | 12.1% | 0.09% | 5.48% | 0.13% | (trace) |
| Tallow | 16,920 | 0.03% | 76.6% | 11.9% | 0.02% | 11.4% | 0.003% | (trace) |
| Tallow Fuel - Oil Blend | 18,523 | 0.06% | 80.7% | 11.9% | 0.01% | 7.22% | 0.13% | (trace) |
| No. 2 Fuel Oil | 19,237 | 0.02% | 84.0% | 11.9% | 0.01% | 3.78% | 0.35% | (trace) |

1) PSC Analytical Services, Reading, PA

## 2.6. General Characterization

The Material Safety Data Sheets (MSDS) included in the Appendix indicate that the fats and greases tested are neither hazardous nor explosive. From the test team's experience, these fats and greases have a distinct and unpleasant odor. However, their volatility is low and the odors do not diffuse readily.

Reports from industry indicate that chicken fat is very miscible in fuel oil and does not readily separate in solution. The test team subjectively confirmed miscibility during the demonstration project; however, definitive data was not collected.

## 2.7. Discussion

Preliminary laboratory analyses indicated that fats and greases could be used with the No. 2 boiler burner nozzle and that the fuel handing system designed for the test program could easily handle these biofuels. Actual combustion testing demonstrated these findings. Later testing confirmed that biofuels, both singly and blended, have high heating value, low ash, and low sulfur content. Heating values for the biofuel blends tested are within 95% of the heating value of No. 2 fuel oil.

The test team concluded that the chicken fat delivered on January 29, 2002 was substandard; the results from the analyses and combustion of this biofuel were omitted from the report. Initially, the particulate content in the chicken fat caused repeated plugging of the fuel handing system filters. Flue gas testing indicated high levels of $NO_x$. Subsequent laboratory analyses showed high levels of insoluble impurities.

Two additional deliveries of chicken fat were ordered and tested. Their particulate content was negligible, and the fuel handling system filters did not plug. Insoluble impurity content and emissions of $NO_x$ were consistent with the other biofuels tested. Insoluble impurities were 20% and $NO_x$ emissions were 66% of that from the initial chicken fat delivery. This report includes the findings from the latter chicken fat deliveries.

These results confirm the need for a high degree of filtration for fats and greases delivered as boiler fuel. Inadequately pre-filtered biofuel causes fuel handing problems and may increase gaseous emissions.

PSC Analytical Services reported problems maintaining data consistency due to the lack of homogeneity of the fuel samples they analyzed. The unblended biofuel samples separated into fractions at room temperature. Heating and stirring of the samples is necessary before they can be analyzed.

Research by Dr. John Goodrum at UGA (see References, Section 8) showed that at 40° C chicken fat, yellow grease, choice white grease and tallow were almost entirely solid. Their liquid-solid transition occurs over 40 – 48° C, and they are all completely liquid by approximately 50° C.

All of the samples (biofuels, both singly and blended, and No. 2 fuel oil) examined by Dr. Goodrum exhibited viscosity that transitioned from non-Newtonian to Newtonian. The viscosity of Newtonian fluids does not vary with shear rate. The viscosity of these fuels initially decreased with increasing shear rate (non-Newtonian fluid behavior), followed by viscosity that became independent of shear rate when the shear rate was increased beyond $12.94s^{-1}$. In other words, the viscosity curves leveled off (viscosity became fairly constant at a given temperature) once the fluid was in motion.

The blends of chicken fat, yellow grease, choice white grease and tallow with No. 2 fuel oil showed rheological properties very similar to those of pure No. 2 fuel oil.

# 3. TEST FACILITY DESCRIPTION

## 3.1. The University of Georgia Steam Plant No. 2 Boiler

All combustion testing was conducted using the No. 2 boiler located at the central steam plant at The University of Georgia campus in Athens, Georgia. Combustion Engineering, Inc. manufactured this boiler in 1970. It was designed to combust natural gas, No. 2 oil and No. 6 oil for the production of 100,000 lbs./hr. of saturated steam at 250 psig. This boiler currently operates at 100 psig. using natural gas, with No. 2 fuel oil as an alternative.

The No. 2 boiler is a pressurized, water-tube design, package unit. It includes a forced-draft fan and a single steam/air atomized fuel nozzle (Todd Combustion, Inc. TCD Atomizer). The TCD Atomizer nozzle was developed in 1958, and does not include air or fuel staging to reduce $NO_x$ formation. This boiler does not have combustion air preheating or an economizer. Flue gas emissions control is not required.

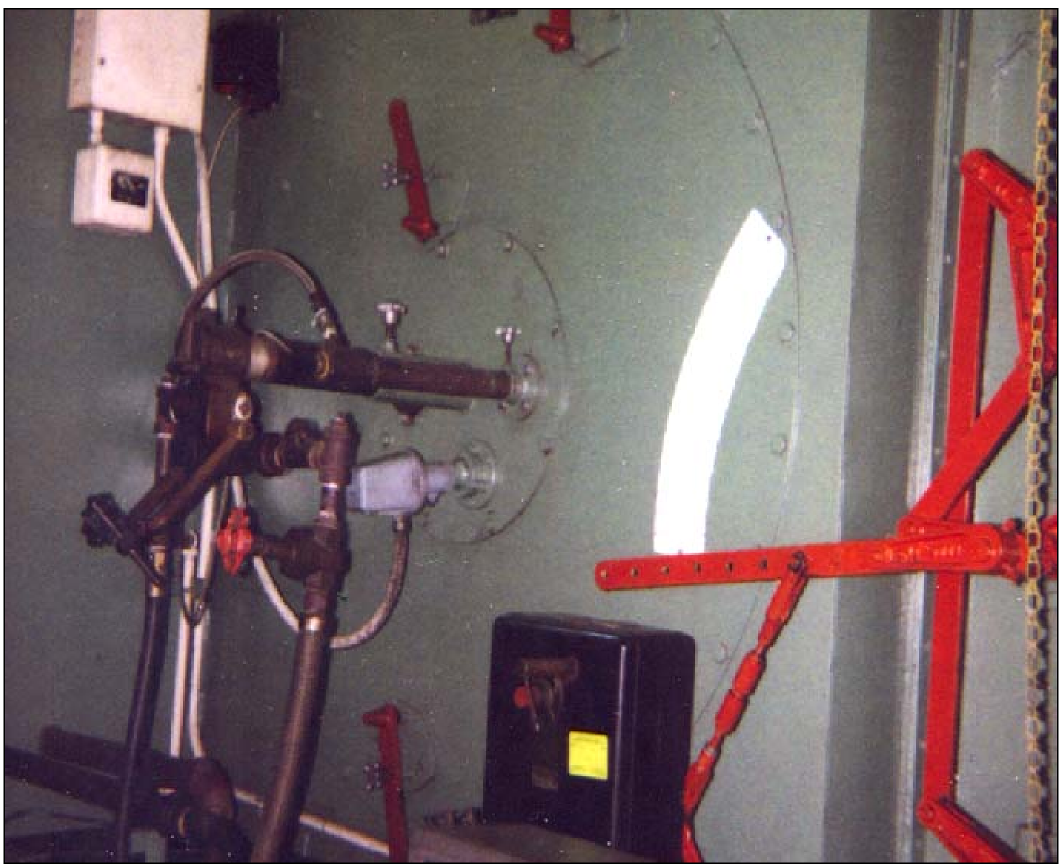


*Fig. 4*, Burner nozzle for the No. 2 boiler

### 3.2. Steam Plant Modifications

Neither the boiler burner nozzle nor the fuel train were changed or modified for the combustion tests. The biofuel handling system was piped into the fuel oil delivery piping upstream of the fuel train. For further details, please refer to the Appendix, Dwg. No. SK-001, *Central Steam Plant Site Plan*, and Dwg. No. SK-002, *Boiler No. 2 Process Flow Diagram*.

A 7 hp gear pump supplied biofuel to the boiler fuel train at a maximum of 22 gpm. A pressure control valve and a safety relief valve maintained the pump discharge pressure to a maximum of 275 psig. Two (2) cast iron basket strainers in parallel protected the pump. A shell and tube heat exchanger, which maintained biofuel temperature, was rated for 150 psig and was installed on the gear pump suction side. 1-1/2" dia. carbon steel sch. 40 piping and 300-lb. malleable iron screwed fittings were used throughout. Some sections of the piping were steam traced.

The biofuel delivery system was manually controlled. Instrumentation consisted of two (2) fuel flow meters, a rotary flow indicator, and necessary pressure and temperature gauges.

The only modification to the boiler was the temporary addition of a flue gas recirculation (FGR) duct and damper. No modifications were made to either the boiler internals or instrumentation.

### 3.3. Fuel Handling System

The biofuel handling system consisted of both mobile equipment and equipment temporarily installed for the tests. Biofuels were transported to the University and stored on site in a 7,000 gallon tanker-trailer. A second tanker trailer was utilized for biofuel/ fuel oil batch mixing. The test protocols were planned so that the quantity of biofuel available at the beginning of each testing period was sufficient for the completion of that test, thus avoiding the complexity of changing fuel supply during a test.

*Fig. 5*, Delivery and mixing tankers at UGA steam plant.

Previous industrial experience had indicated that after a 24 hour exposure to extreme winter ambient temperatures, a 7,000 gallon tanker load of biofuel could become too viscous for handling. Therefore, all biofuel was delivered warm (over 100° F) and within 4 hours after loading. All biofuel suppliers were located near Atlanta, GA, less than 80 miles from the steam plant. Delivery tankers were piped to the fuel system immediately after they arrived at the UGA steam plant. The fuel system continuously recirculated the biofuel to the tanker and kept it warm and mixed.

A heat exchanger was included in the fuel handling system prior to fuel transfer to the boiler. The heat exchanger maintained the biofuel temperature to approximately 165° F to reduce its viscosity to that of No. 2 fuel oil. The source of heat for this unit was 5 psig steam.

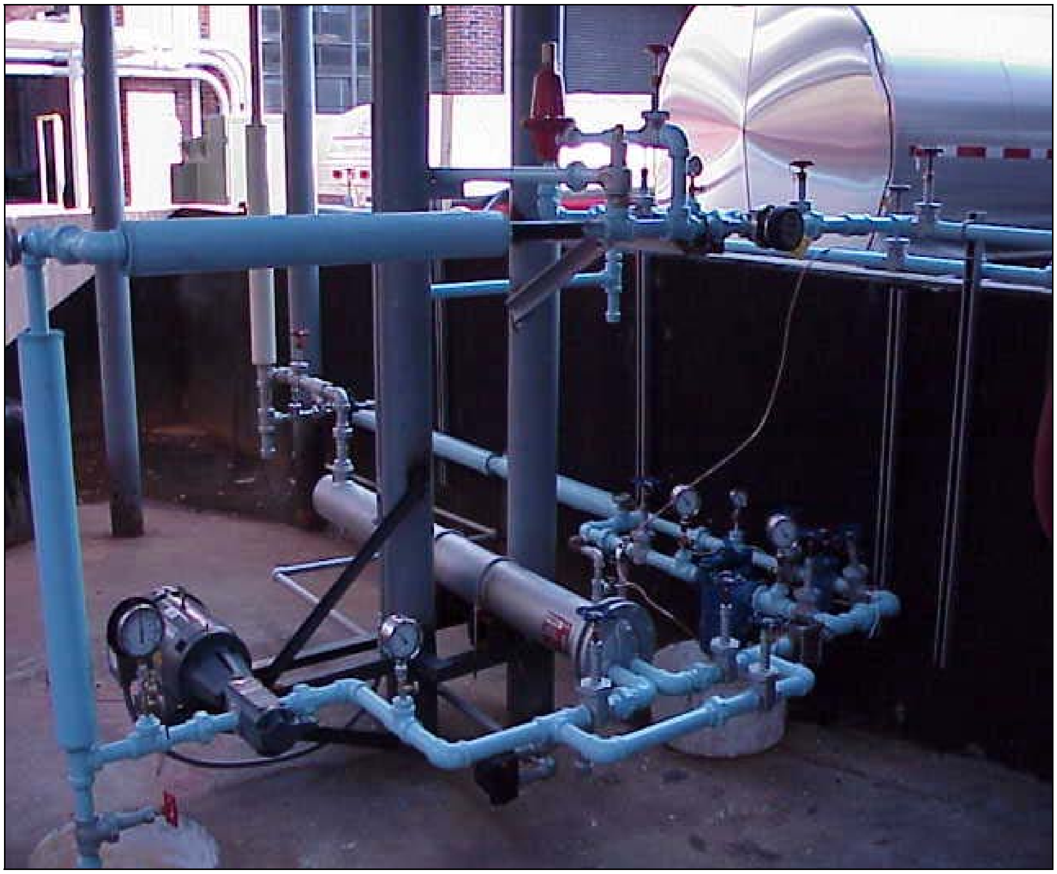


*Fig. 6*, Fuel heating, pumping and mixing system.

3.4. Flue Gas Recirculation System

The FGR system consisted of a 20 inch diameter duct connecting the boiler flue gas breaching (at 0.0 in. wg. static pressure) and the forced draft fan inlet (at negative 0.25 in. wg. static pressure). An adjustable butterfly damper was installed in the duct to control flow. Pitot tube flow measurements indicated that 7 to 10% of the flue gas exiting the boiler was recirculated back into the burner.

3.5. Environmental Protection

Provisions were made to maintain personnel safety and to avoid and control spills in accordance with the UGA Spill Prevention Control and Countermeasure Plan (SPCCP) and the UGA Storm Water Pollution Prevention Plan (SWPPP). The biofuel transfer pump, two fuel strainers, and the heat exchanger were located in a diked containment area to isolate them from the sanitary sewer system.

# 4. COMBUSTION DEMONSTRATION

## 4.1. Introduction

Industrial boiler operating experience and data were obtained while firing natural gas, No. 2 fuel oil, biofuels, and biofuels blended with No. 2 fuel oil. Baseline combustion testing was conducted by firing natural gas and fuel oil. Testing was conducted both with and without flue gas recirculation and with a range of boiler loads to evaluate emissions and combustion efficiencies under a wide range of operating conditions. The tests demonstrated that the biofuels burn efficiently, cleanly, readily, without odor and without damage to boiler equipment.

## 4.2. Test Schedule

The University of Georgia in Athens, GA is subject to mild winter conditions and considers the winter heating season to extend from late November to mid-February. Steam demand on the central steam plant is in the 100,000 to 200,000 lb/hr range during the winter heating season. This demand reduces to less than 50,000 lb/hr during the summer. Throughout the year, daily load peaks in the early morning.

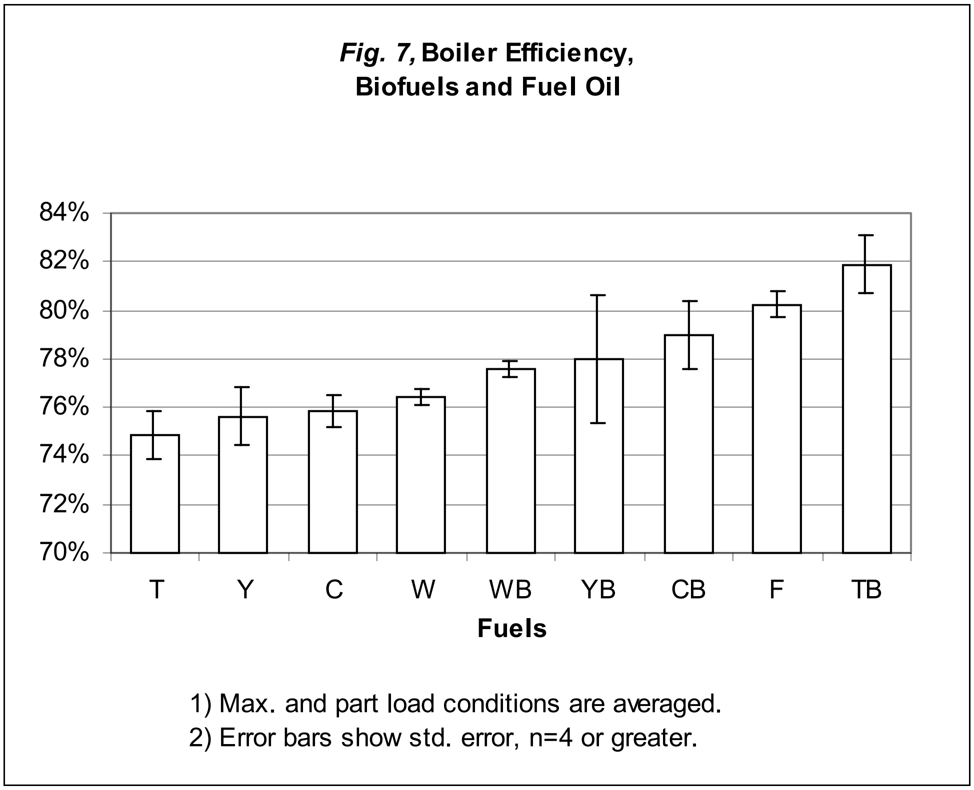
The project team scheduled the tests during the winter heating season to allow for testing of the No. 2 boiler at maximum load. The tests began January 28, 2002 and continued daily for three weeks until February 15, 2002. Maximum load tests were conducted in the morning, part load tests in the afternoon. A follow-up test on chicken fat was conducted on March 15, 2002.

In general, the sequence of the testing was chicken fat and blend, yellow grease, choice white grease and blend, tallow, yellow grease blend and tallow blend. All blends consisted of 33% fat or grease and 67% No. 2 fuel oil. Natural gas and No. 2 fuel oil testing was conducted periodically throughout the test period.

## 4.3. Boiler Efficiency

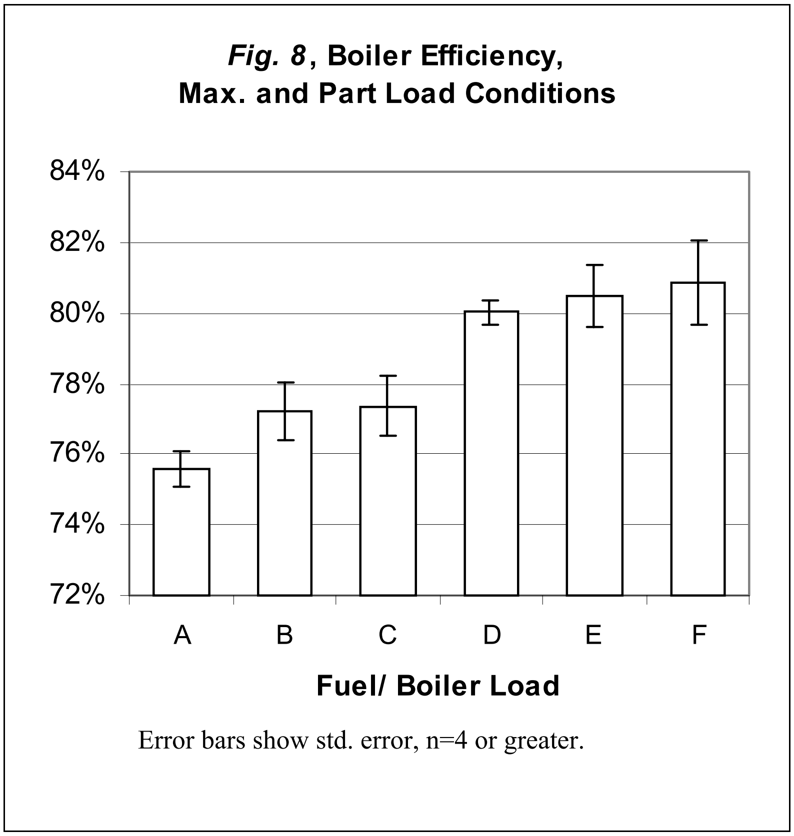
Boiler efficiency is calculated as boiler steam energy output (btu/hr), less feedwater energy input, as a percentage of boiler fuel energy input (btu/hr). Steam plant instrumentation measured the flow (lb/hr) and pressure (psig) of the saturated steam produced by the boiler. Feedwater energy input was based on the temperature at the deaerator.

Fuel energy input is the product of the flowrate and the energy content of the fuel. The flowrate was determined from the flow at the boiler burner nozzle flowmeter divided by the time interval between meter readings. PSC Analytical Services analyzed samples of each fuel to determine specific energy content.




| Fuel Abrev. | Average Efficiency | Fuels |
|---|---|---|
| T | 74.9% | TALLOW |
| Y | 75.6% | YELLOW GREASE |
| C | 75.9% | CHICKEN FAT |
| W | 76.4% | CHOICE WHITE GREASE |
| WB | 77.6% | CHOICE WHITE GREASE - FUEL OIL BLEND |
| YB | 78.0% | YELLOW GREASE - FUEL OIL BLEND |
| CB | 79.0% | CHICKEN FAT - FUEL OIL BLEND |
| F | 80.2% | No. 2 FUEL OIL |
| TB | 81.9% | TALLOW - FUEL OIL BLEND |

*Fig. 7*, Legend

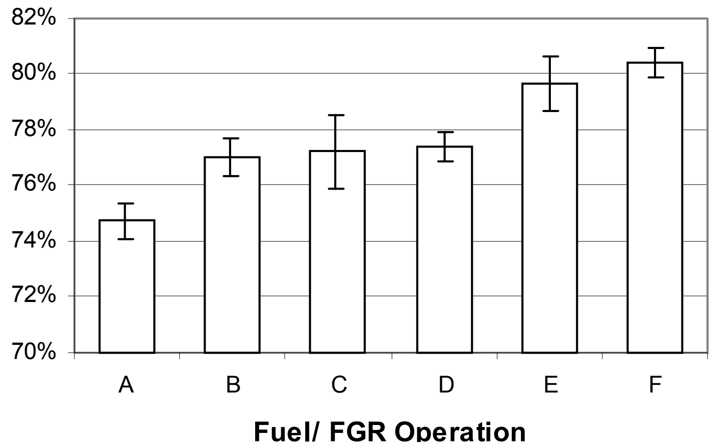



| Fuel/ Load | Average Efficiency | Fuel & Boiler Loading |
|---|---|---|
| A | 75.6% | BIOFUELS @ MAX. LOAD |
| B | 77.2% | BIOFUELS @ PART LOAD |
| C | 77.4% | BLENDED BIOFUELS @ MAX. LOAD |
| D | 80.0% | No. 2 FUEL OIL @ MAX. LOAD |
| E | 80.5% | No. 2 FUEL OIL @ PART LOAD |
| F | 80.9% | BLENDED BIOFUELS @ PART LOAD |

*Fig. 8*, Legend

There was no significant difference in boiler efficiency when using 100% #2 fuel oil and blends with 33% biofuel oil according to a Student's t-test at the $\alpha = 0.05$ significance level. Boiler efficiency of #2 fuel oil was significantly higher compared to biofuel oil alone. Boiler efficiency was significantly higher using tallow blend compared to #2 fuel oil under half load conditions.

***Fig. 9*, Boiler Efficiency, with and w/o FGR**




1) Maximum boiler load conditions shown.
2) Error bars show std. error, n=4 or greater.
3) 1% error assumed for case E.

| Fuel/ FGR. Operation | Average Efficiency | Flue Gas Recirculation (FGR) Status |
|---|---|---|
| A | 74.7% | BIOFUELS, w/o FGR |
| B | 77.0% | BIOFUELS with FGR |
| C | 77.2% | BLENDED BIOFUELS w/o FGR |
| D | 77.4% | BLENDED BIOFUELS with FGR |
| E | 79.6% | No. 2 FUEL OIL w/o FGR |
| F | 80.4% | No. 2 FUEL OIL with FGR |

*Fig. 9*, Legend

## 4.4. Combustion Characteristics

The steam plant did not experience any unusual operating problems while burning biofuel or biofuel blends. The boiler lit off quickly and ran quietly. There were no fat and grease odors in the plant.

Observations through the furnace sight glasses indicated that biofuels generally burn with a flame that is more yellow-colored and widely dispersed than with either natural gas or No. 2 fuel oil. However, the flame pattern was well contained within the furnace, as was verified by later internal inspection of the furnace.

At maximum load, fuel pressure to the boiler nozzle averaged 160 psig for unblended biofuels, 157 psig for blended biofuels, and 119 psig for No. 2 fuel oil. Atomizing steam pressure averaged 97 psig under all conditions.

A thermocouple was installed in the furnace to measure its internal temperature. The thermocouple projected approximately 3 ft. into the back of the furnace, at the flue gas backpass. Temperature readings were read from a handheld digital thermometer.

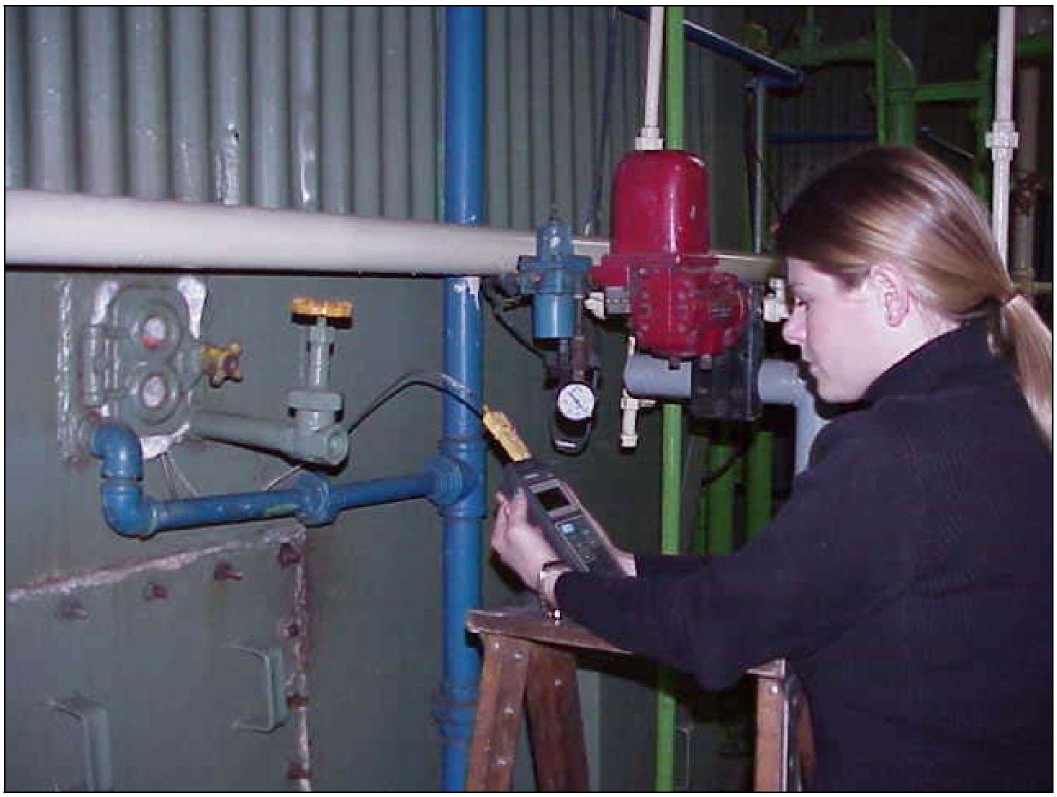


*Fig. 10*, Furnace temperature measurement system

## 4.5. Inspection of Boiler Internals

The test team inspected the interior of the boiler after several months of firing natural gas exclusively; then, after firing No. 2 fuel oil exclusively; and, finally, after three weeks of biofuel combustion testing. The test team observed that the water tube exterior surfaces were clean and soot-free after natural gas firing. The tube surfaces were soot-covered, black-colored, and somewhat greasy after firing with No. 2 fuel oil.

Following biofuel burning, the interior of the furnace appeared to be almost as clean as it was after firing natural gas, and much cleaner than it was after burning No. 2 fuel oil. A slight blackening of the tube surfaces, following the flame pattern, was observed in the front half of the 25-ft. long furnace.

A scattering of baked-on solid deposits (each approximately 2-3 mm in diameter) was found on the tube surfaces in the back half of the furnace. The UGA Chemical Analysis Laboratory analyzed three (3) samples of this material with an ICP mass spectrometer and found that they consist predominately of the elements Fe, Na, P, K, and Ca.

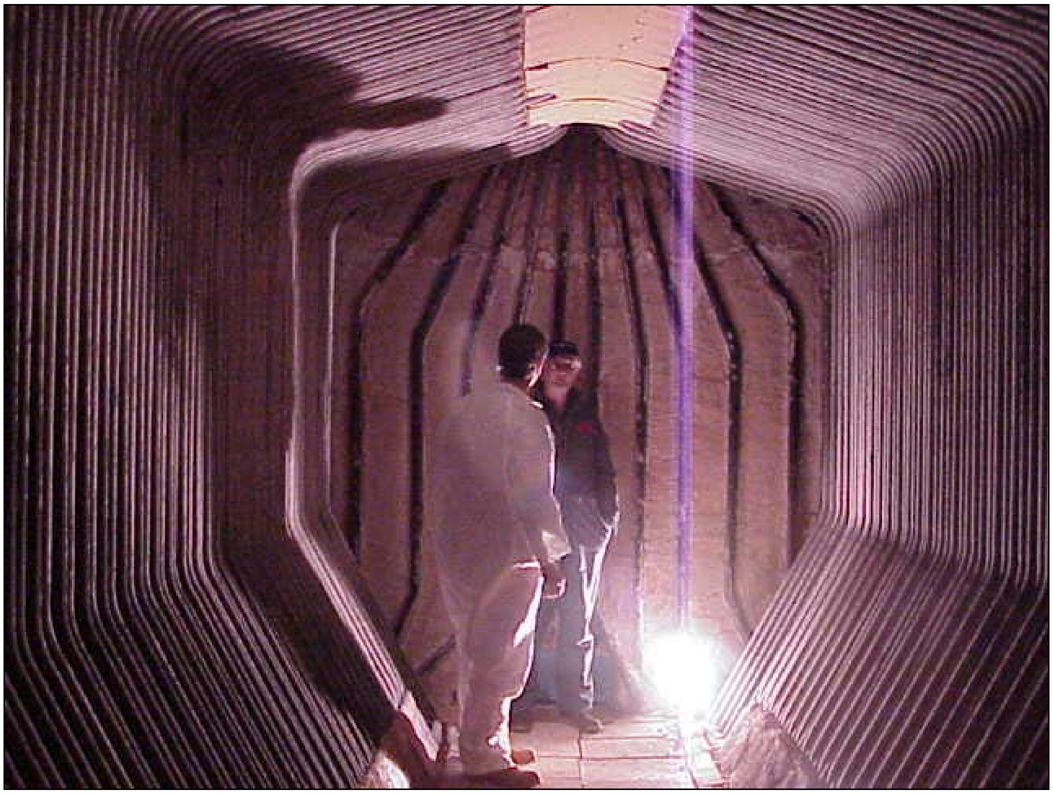


*Fig. 11*, Inspection of boiler heat transfer surfaces after testing biofuels

4.6. Discussion

The standard error calculated for the efficiency data ranged from 0.3% to 1.4%, plus or minus, with one data point showing a 2.6% +/- standard error, n = 4. The instrumentation used is standard industrial class equipment, and was not specially calibrated for this test. The greatest potential for error is the time recording taken between fuel meter readings. A time interval of 13 minutes was the minimum used. All time readings were taken with a wristwatch to the nearest minute.

There was no significant difference in efficiency under part load conditions versus full load according to an unpaired Student's t-test at the $\alpha = 0.05$ significance level. Also, there was no significant difference in efficiency with or without FGR. However, combustion with FGR resulted in significantly less excess air in the flue gas and indicates more complete combustion and less loss of energy to the stack.

# 5. EMISSIONS TESTING

## 5.1. Particulate Testing

Advanced Air Consultants Inc. (AAC), Murrayville, GA performed emissions tests for condensible (both organic and inorganic) and non-condensible particulate. Two test runs, each one hour long and conducted under normal boiler operation, were performed on each of five different fuels (chicken fat, yellow grease, choice white grease, tallow, and No. 2 fuel oil). Simultaneously with the particulate tests, the UGA Engineering Outreach test team measured gaseous emissions.

AAC conducted all particulate testing according to the reference methods developed by the US EPA and promulgated in the Code of Federal Regulations, Title 40, Parts 51 and 60. AAC is certified per NELAC procedures to perform EPA Method 5 particulate measurement. All of the test equipment was manufactured and calibrated as specified in the EPA methods.

The particulate testing location was in a straight section of the No. 2 boiler breaching, between the boiler and a combined boiler stack. The number of velocity traverse points was chosen based on the distance of the test ports from up and downstream flow disturbances. Flow disturbances were located 2.5 diameters upstream and 1.0 diameters downstream from the test ports. Twenty traverse points were sampled.

*Fig. 12.* Inserting particulate testing probe into breaching.

AAC used a sampling train consisting of a stainless steel nozzle, stainless steel union, stainless steel lined probe, glass filter holder with Teflon filter support, four glass impingers, umbilical cord, vacuum pump, dry gas meter and orifice. Both the probe and filter compartment were heated to 250 deg. F. The impingers were placed in an ice bath to remove moisture from the sample gas stream. A "S" type pitot tube and an inclined manometer measured the gas velocity pressures. A type K thermocouple and a digital thermometer measured the gas temperature. The Denver Instruments Model A-250 analytical balance in the AAC laboratory weighed the particulate samples.

In accordance with US EPA Method 19 (40CFR60), AAC calculated fuel F-Factors using the fuel analysis data presented in Section 3 of this report. F-Factors are used to calculate emission rates in pounds per million Btu, per US EPA methodology.

The US EPA "F Factor" technique is a more convenient method to determine emissions on a mass per unit heat input basis. This technique allows the calculation of emissions without the need for precise measurement of fuel flow and combustion efficiency.

***Table 4*, F-Factors**

| Fuel | F-Factor, Fd |
|---|---|
| Chicken Fat | 8,865 |
| Yellow Grease | 9,108 |
| Choice White Grease | 9,145 |
| Tallow | 9,179 |
| No. 2 Fuel Oil | 8,850 |

Source: Advanced Air Consultants, Inc., Murrayville, GA

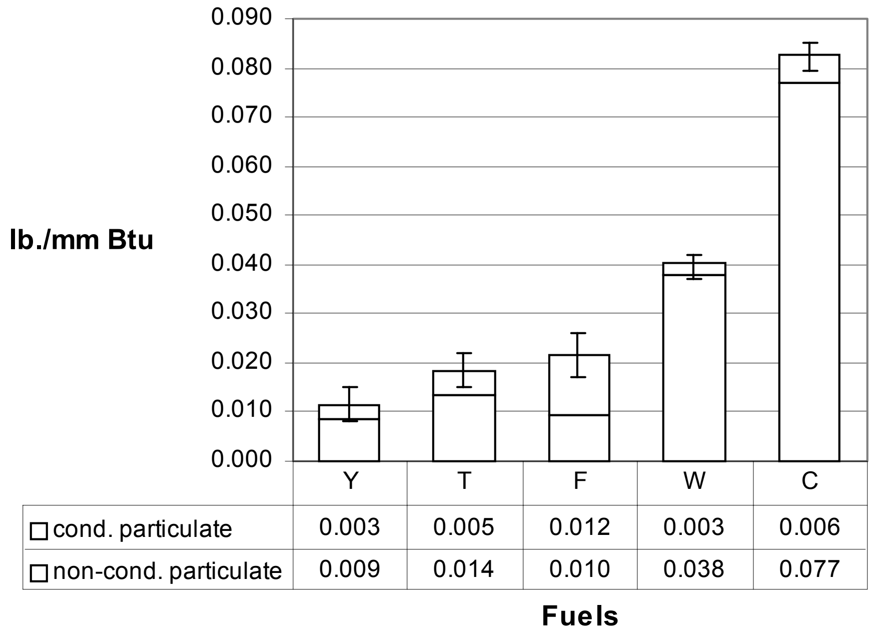
Fd is the ratio of the quantity of dry effluent gas generated by combustion to the gross calorific value of the fuel, dscf/$10^6$Btu.

Ref.: *Federal Register*, 40:194, Part V, Oct. 6, 1975,

AAC also monitored smokestack opacity. Maximum opacity with chicken fat was 4% and yellow grease was 6%. There was no opacity observed while burning tallow. Opacity was not monitored while burning choice white grease.

Opacity testing was not performed in strict accordance with GA EPD compliance regulations, which require an average value for a series of opacity observations over a one-hour period. Instead, opacity testing during the program consisted of a series of spot observations. However, all opacity readings were taken by GA EPD-certified opacity readers.

*Fig. 13*, **Particulate Emissions, Biofuels and Fuel Oil**




1) Test conditions: maximum boiler load with FGR.
2) Condensible particulate = organic + inorganic condensible particulate.
3) Total particulate = non-cond. + cond. particulate.
4) Error bars show std. error for total particulate.

| Fuel Abrev. | Fuel |
|---|---|
| Y | YELLOW GREASE |
| T | TALLOW |
| F | No. 2 FUEL OIL |
| W | CHOICE WHITE GREASE |
| C | CHICKEN FAT |

*Fig. 13.* Legend

## 5.2. Gaseous Emissions Testing

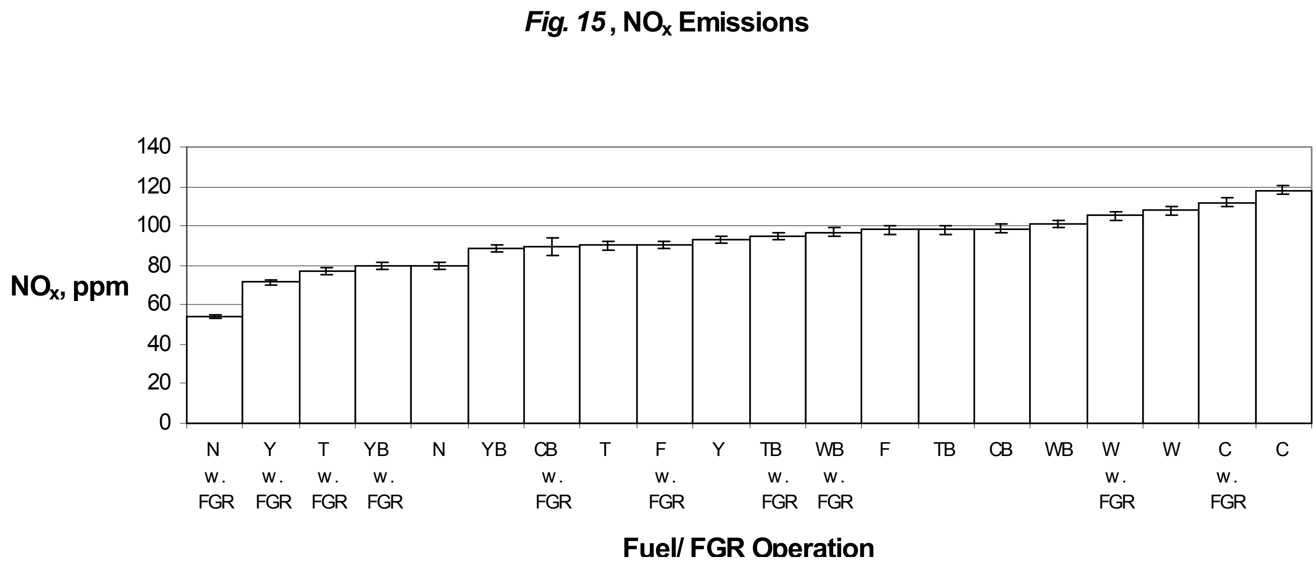
The UGA Engineering Outreach team used an ENERAC 3000E analyzer to measure the gaseous emissions from the No. 2 boiler. The team recorded both average and instantaneous measurements of flue gas concentrations for oxygen, carbon monoxide, carbon dioxide, combustible gases, excess air, nitric oxide, nitrogen dioxide, $NO_x$ ($NO + NO_2$), and sulfur dioxide. The analyzer software program enabled the recording of emissions data directly to a spreadsheet file on the hard drive of a laptop computer. Data was recorded during steady state operations for each fuel tested, at both maximum and part loads and at each FGR damper setting.

The ENERAC 3000 portable emissions analyzer is a self-contained, extractive flue gas monitoring system utilizing electrochemical sensors with an internal sample pump designed for 600-900 cc/minute. A separate vacuum pump extracted flue gas from a breaching port and discharged it to the ENERAC. Teflon tubing interconnected a filter probe in the breaching through two moisture condensers to the vacuum pump and then to the analyzer.

The ENERAC sensors use an electronically controlled circuit to minimize zero drift and reject cross interference from other compounds, in compliance with EPA Conditional Test Methods (CTM) –022, -030 and –034. The performance specifications of the CTM-022 method are equivalent to US EPA Method 7E requirements. The accuracy of the sensors is +/-2%, and they are capable of operating at 1.5 orders of magnitude of gas concentrations.

Equipment was calibrated several times per week, and was checked daily for accuracy. The system was allowed to autozero daily. Span calibration of CO, NO, SO, $NO_2$ was performed 2-3 times per week using calibrated gases (CO at 78 ppm, NO at 124 ppm, $SO_2$ at 25 ppm, and $NO_2$ at 92 ppm.)

*Fig. 14.* Logging of emissions data from Enerac 3000E.

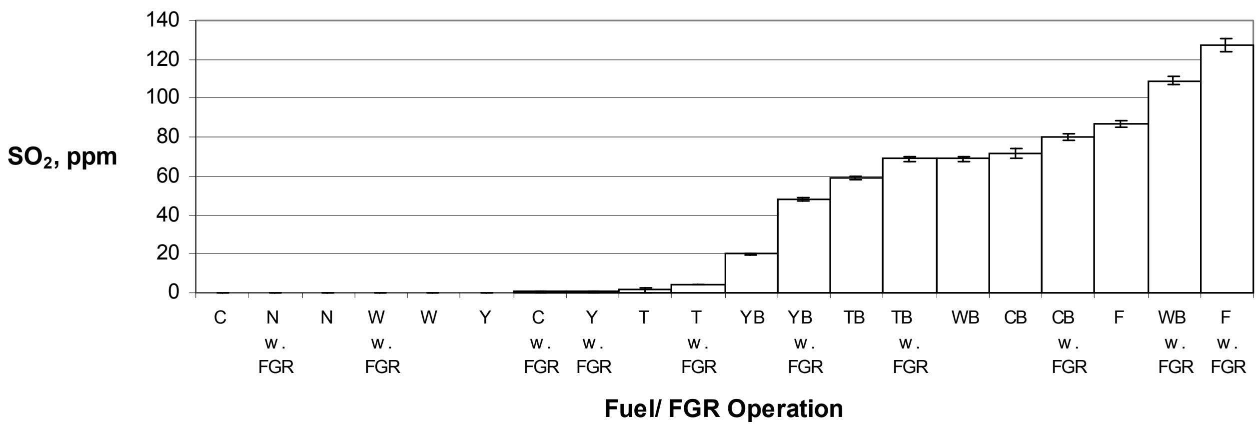



1) All tests were conducted at maximum boiler load.
2) Error bars show std. error calculated for cases: CB with FGR (n=2) and T w/o FGR (n=3). 2% error assumed for all of the other cases.

| Fuel | Legend | NOx emissions, ppm | | | Furnace Temperature, deg. F. | | |
|---|---|---|---|---|---|---|---|
| | | w/o FGR | w. FGR | % reduction | w/o FGR | w. FGR | delta |
| N | NATURAL GAS | 80 | 54 | 32.5% | 1,983 | 2,010 | 27 |
| Y | YELLOW GREASE | 93 | 71 | 23.7% | 1,755 | 1,830 | 75 |
| T | TALLOW | 90 | 77 | 14.4% | 1,824 | 1,928 | 104 |
| YB | YELLOW GREASE - FUEL OIL BLEND | 89 | 80 | 10.1% | 1,773 | 1,811 | 38 |
| CB | CHICKEN FAT - FUEL OIL BLEND | 99 | 90 | 9.1% | 1,756 | 1,843 | 87 |
| F | No. 2 FUEL OIL | 98 | 91 | 7.1% | 1,836 | 1,901 | 65 |
| TB | TALLOW - FUEL OIL BLEND | 98 | 95 | 3.1% | 1,714 | 1,790 | 76 |
| WB | CHOICE WHITE GREASE - FUEL OIL BLEND | 101 | 97 | 4.0% | 1,860 | 1,954 | 94 |
| W | CHOICE WHITE GREASE | 108 | 105 | 2.8% | 1,855 | 1,886 | 31 |
| C | CHICKEN FAT | 118 | 112 | 5.1% | 1,776 | n.a. | n.a. |

*Fig. 15.* Legend

***Fig. 16*, $SO_2$ Emissions**

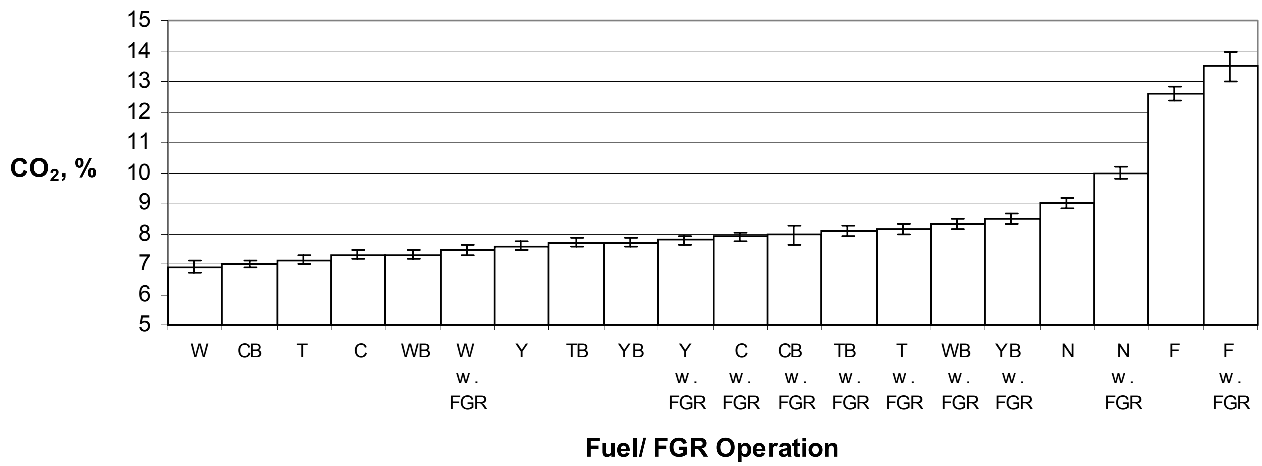



1) All tests were conducted at maximum boiler load.
2) Error bars show std. error (n=2 or greater) calculated for cases: Y, YB, F, W, and C with FGR; and cases T, CB and W w/o FGR. 2% error assumed for all of the other cases.

| Fuel | Legend | $SO_2$ emissions, ppm | | |
|---|---|---|---|---|
| | | w/o FGR | w. FGR | delta |
| N | NATURAL GAS | 0 | 0 | 0 |
| Y | YELLOW GREASE | 0 | 1 | 1 |
| W | CHOICE WHITE GREASE | 0 | 0 | 0 |
| C | CHICKEN FAT | 0 | 0 | 0 |
| T | TALLOW | 1 | 4 | 3 |
| YB | YELLOW GREASE - FUEL OIL BLEND | 20 | 48 | 28 |
| TB | TALLOW - FUEL OIL BLEND | 59 | 69 | 10 |
| WB | CHOICE WHITE GREASE - FUEL OIL BLEND | 69 | 109 | 40 |
| CB | CHICKEN FAT - FUEL OIL BLEND | 72 | 80 | 8 |
| F | No. 2 FUEL OIL | 87 | 127 | 40 |

*Fig. 16.* Legend

**Fig. 17, $CO_2$ Emissions**

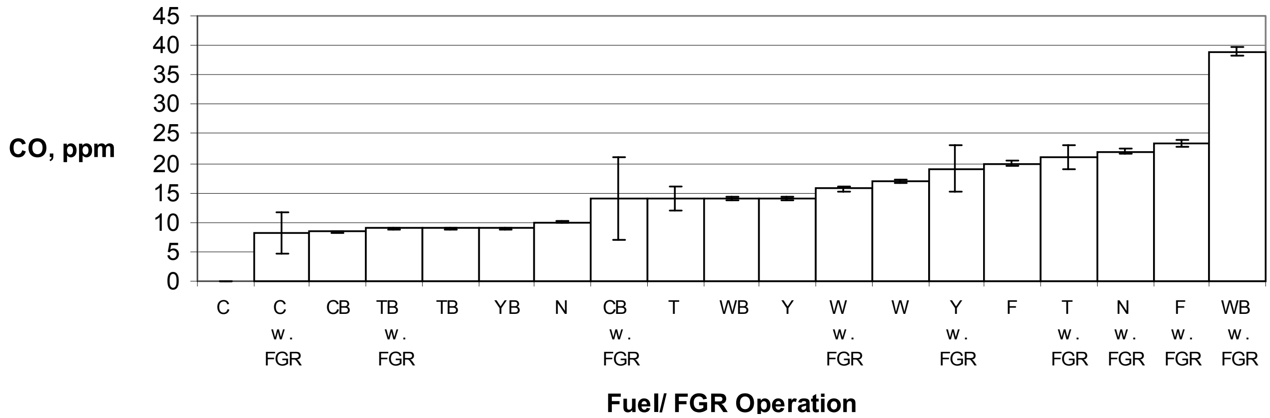



1) All tests were conducted at maximum boiler load.
2) Error bars show std. error (n=2 or greater) calculated for cases: CB, F, and W with FGR, and T and W w/o FGR.
3) 2% error assumed for all of the other cases.

| Fuel | Legend | $CO_2$ emissions, % | | |
|---|---|---|---|---|
| | | w/o FGR | w. FGR | delta |
| W | CHOICE WHITE GREASE | 6.9 | 7.5 | 0.6 |
| CB | CHICKEN FAT - FUEL OIL BLEND | 7.0 | 8.0 | 1.0 |
| T | TALLOW | 7.1 | 8.2 | 1.1 |
| C | CHICKEN FAT | 7.3 | 7.9 | 0.6 |
| WB | CHOICE WHITE GREASE - FUEL OIL BLEND | 7.3 | 8.3 | 1.0 |
| Y | YELLOW GREASE | 7.6 | 7.8 | 0.2 |
| TB | TALLOW - FUEL OIL BLEND | 7.7 | 8.1 | 0.4 |
| YB | YELLOW GREASE - FUEL OIL BLEND | 7.7 | 8.5 | 0.8 |
| N | NATURAL GAS | 9.0 | 10.0 | 1.0 |
| F | No. 2 FUEL OIL | 12.6 | 13.5 | 0.9 |

*Fig. 17.* Legend

*Fig. 18*, **CO Emissions**

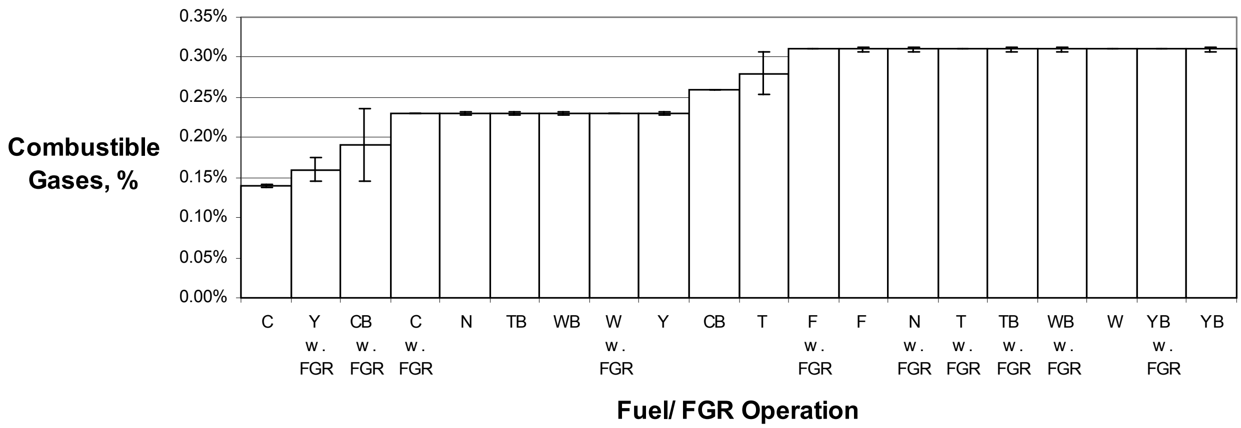



1) All tests were conducted at maximum boiler load.
2) Error bars show std. error (n=2 or greater) calculated for cases: Y, T, CB, F, W, and C with FGR, and T w/o FGR. 2% error assumed for all of the other cases.

| Fuel | Legend | CO emissions, ppm | | |
|---|---|---|---|---|
| | | w/o FGR | w. FGR | delta |
| C | CHICKEN FAT | 0 | 8 | 8 |
| CB | CHICKEN FAT - FUEL OIL BLEND | 8 | 14 | 6 |
| TB | TALLOW - FUEL OIL BLEND | 9 | 9 | 0 |
| YB | YELLOW GREASE - FUEL OIL BLEND | not available | | |
| N | NATURAL GAS | 10 | 22 | 12 |
| T | TALLOW | 14 | 21 | 7 |
| WB | CHOICE WHITE GREASE - FUEL OIL BLEND | 14 | 39 | 25 |
| Y | YELLOW GREASE | 14 | 19 | 5 |
| W | CHOICE WHITE GREASE | 17 | 16 | -1 |
| F | No. 2 FUEL OIL | 20 | 23 | 3 |

*Fig. 18.* Legend

***Fig. 19*, Combustibles in Flue Gas**




1) All tests were conducted at maximum boiler load.
2) Error bars show std. error (n=2 or greater) calculated for cases: Y, T, YB, CB, F, W, and C with FGR; and cases T, CB and W w/o FGR.
3) 2% error assumed for all of the other cases.

| Legend | Combustibles in Flue Gas, % | | |
|---|---|---|---|
| | w/o FGR | w. FGR | delta |
| CHICKEN FAT | 0.14% | 0.23% | 0.09% |
| NATURAL GAS | 0.23% | 0.31% | 0.08% |
| TALLOW - FUEL OIL BLEND | 0.23% | 0.31% | 0.08% |
| CHOICE WHITE GREASE - FUEL OIL BLEND | 0.23% | 0.31% | 0.08% |
| YELLOW GREASE | 0.23% | 0.16% | -0.07% |
| CHICKEN FAT - FUEL OIL BLEND | 0.26% | 0.19% | -0.07% |
| TALLOW | 0.28% | 0.31% | 0.03% |
| No. 2 FUEL OIL | 0.31% | 0.31% | 0.00% |
| CHOICE WHITE GREASE | 0.31% | 0.23% | -0.08% |
| YELLOW GREASE - FUEL OIL BLEND | 0.31% | 0.31% | 0.00% |

*Fig. 19.* Legend

## 5.3. Odor Sampling

At no time during the demonstration program did the test team receive any complaints about odor originating from the steam plant. Test team members, BAE faculty and staff associated with the project, and the steam plant personnel (10 individuals, in total) monitored the campus for odor and recorded their findings at least twice for each test series. Odor was monitored (36) times throughout the demonstration program. Each odor test began at the steam plant; and, if the wind speed exceeded 1 to 2 mph, was repeated again 0.5 to 1.0 miles down wind of the steam plant. A check of the UGA campus weather website preceding each test confirmed the wind direction and velocity. All odor testers were asked to verify that they were not suffering from any nasal congestion.

Odor was not detected during any of the (17) tests taken down wind of the steam plant. However, there were noticeable fat and grease odors detected in the vicinity (within 100 ft.) of the biofuel tankers.

## 5.4. Flue Gas Recirculation (FGR) Flow Measurement

Approximately 7 to 10 % of the boiler breaching flue gas was recirculated to the forced draft fan inlet with the recirculation damper 100% open. The test team performed a series of flowrate measurements using standard pitot tube traverse methodology. Measurements were made for all fuels, at both full and part load conditions.

The arrangement of the FGR ducting made pitot traversing difficult and impeded the accuracy of the tests. However, the tests are deemed accurate within 25%, which is sufficient to determine that the system was functioning.

## 5.5. Discussion

The most significant source of data inaccuracy during the particulate testing is the % of isokinetic sampling, which is the ratio of flue gas flow rate to the sampling flow rate. The GA EPD allows these rates to average within 10% of each other during a one-hour sample period, i.e., a test accuracy of 10%+/-. For compliance testing, two out of three samples must meet the 10% criteria. During this test program, at least one particulate test for each fuel met the EPD requirement.

Odor and opacity test readings were subjective. Their degree of accuracy cannot be documented. Statistical analysis using the Student's t-test statistic was used to test for significant difference ($\alpha = 0.05$) for other data using Sigma-Plot version 2.01 software (Jandel Corporation, San Raphael, CA).

Total particulate emissions from biofuel oil as a group were not significantly different from particulate emissions from #2 fuel oil. However, total particulate emissions from chicken fat fuel was significantly higher than the other biofuel oils and both chicken fat and choice white fat particulate emissions were significantly higher than #2 fuel oil. Particulate emissions from chicken fat fuel were significantly higher than those from choice white grease.

In general, the most significant source of data inaccuracy during gaseous emission testing is the specified 2%+/- accuracy of the ENERAC sensors.

Most of the $NO_x$ formed during combustion is from high temperature oxidation of atmospheric nitrogen. This $NO_x$ is referred to as "thermal $NO_x$ and is popularly modeled as an exponential function of flame temperature and a square root function of oxygen concentration. Thus, the formation of thermal $NO_x$ can be controlled by manipulating the flame temperature or the oxygen concentration (Agrawal and Wood, 2002). Average emissions of $NO_x$ from the combustion of all biofuel oils were not found to be significantly different than emissions from #2 fuel oil (Student's unpaired t-test, 0.05 significance level). However, the $NO_x$ emissions from chicken fat alone were significantly higher than the other biofuel oils and #2 fuel oil and natural gas. This result is confounding, the chicken fat fuel contained higher ash (Table 3), however, total nitrogen was low and combustion conditions were identical to the other combustion tests.

The procedures used in this testing of FGR both reduced oxygen (which decreases $NO_x$) and increased furnace temperature (which increases $NO_x$, see *Fig. 15,* Legend). The net result was that for all cases when flue gas recirculation was used, $NO_x$ decreased in the range of 2.8% to 32.5%, significantly different from emissions without FGR according to a Student's paired t-test ($\alpha = 0.05$). The discrepancy between the factors simultaneously driving the increase and the decrease of $NO_x$ should be further studied.

The ENERAC may have recorded $SO_2$ readings significantly lower than actual. Gas samples extracted from the breaching were cooled below the $SO_2$ condensation temperature (to remove excess moisture) before the sample was analyzed by the ENERAC. However, the relative $SO_2$ data values presented in *Fig. 16* are considered valid because this data is proportional to % sulfur analyzed in the fuels. The biofuel oils had practically zero amounts of $SO_2$ in emissions and they were significantly less than the biofuel oil blends and #2 fuel oil. Additionally, biofuel oil blends had significantly lower $SO_2$ emissions that #2 fuel oil.

There were significantly lower $CO_2$ emissions from biofuel oil versus #2 fuel oil. Additionally, 33% blends of biofuel oil in #2 fuel oil had significantly lower $CO_2$ emissions.

There was no significant difference in CO emissions between the biofuel oils, blends, or #2 fuel oil. FGR had no significant effect on CO or combustibles emissions. Chicken fat and yellow grease emissions were significantly lower in combustibles than #2 fuel oil.

## 6. CONCLUSIONS

Fats and greases were demonstrated as industrial boiler fuels. These biofuels easily and economically displace No. 2 fuel oil using the same boiler operating procedures as fuel oil without any modifications to internal boiler combustion equipment. The biofuels need to be kept warm during cold weather in order to flow through piping and equipment. When heated to about 160° F. biofuels are easily atomized and ignited. Construction costs for the pump, heat exchanger, instruments, piping, valves, fittings, and electrical system for a system to maintain the 160° F. temperature and to transfer fuel from storage to the boiler was less than $31,000. This total does not include the cost of engineering or the procurement cost for the heat exchanger. Extra costs would be incurred if separate storage tanks were needed for biofuel storage. Research should be accomplished focusing on the issues associated with using existing No. 2 fuel oil storage tanks for the storage of biofuel and biofuel blends.

Air emissions from the combustion of the biofuel oils met or exceeded state and federal air quality permit requirements for The University of Georgia. Nitrogen oxides and particulate emissions were comparable to emissions from the combustion of No. 2 fuel oil, Table 4. Sulfur dioxide emissions and deposits on boiler tubes were similar to those encountered when burning natural gas. Biofuels also have low carbon monoxide emissions. The fuel nozzle used in the UGA boiler was a 1950's design and no special procedures were used to minimize emissions through nozzle placement. Flue gas recirculation (FGR) was tested with 7% to 10% of flue gas being recirculated. FGR did not significantly increase boiler efficiency but did significantly reduce $NO_x$ emissions compared to tests without FGR according to a Students t-test at the $\alpha = 0.05$ significance level. $NO_x$ emissions were not reduced enough to meet regulations for new sources and for non-attainment areas. Additional testing is required using low $NO_x$ nozzle designs and other methods for minimizing emissions. When the boiler was operated at half load, boiler efficiency was significantly greater for a blend of 33% tallow with 77% #2 fuel oil than when using 100% #2 fuel oil ($\alpha = 0.05$).

The biofuel oils have high heating value; low amounts of ash, nitrogen, and moisture; and negligible amounts of sulfur. Heating values of the biofuel oil blends tested are within 95% of the heating value of No. 2 fuel oil. The specific gravity of the biofuels is close to that of No. 2 fuel oil. The biofuels are more viscous than No. 2 fuel oil, but much less viscous than No. 6 fuel oil. However, a blend of 30% biofuel with No. 2 fuel oil has a viscosity that is close to that of No. 2 fuel oil. Boiler efficiency while burning biofuel oil is comparable to that of No. 2 fuel oil.

***Table 5*, Comparison of UGA Test Emissions to US EPA Criteria Pollutant Emission Factors**

| Fuel & Firing Condition | $NO_x$, lb./MMBtu | Filterable PM, lb./MMBtu | CO, lb./MMBtu | $SO_2$, lb./MMBtu [5] |
|---|---|---|---|---|
| **UGA Boiler No. 2 Emissions, Tested at Max. Steam Load [1]:** | | | | |
| Chicken Fat, controlled with FGR [7] | 0.156 | 0.077 | 0.008 | 0.000 |
| Yellow Grease, controlled with FGR [7] | 0.097 | 0.009 | 0.016 | 0.001 |
| Choice White Grease, controlled with FGR [7] | 0.150 | 0.038 | 0.014 | 0.000 |
| Tallow, controlled with FGR [7] | 0.101 | 0.014 | 0.018 | 0.007 |
| No. 2 Fuel Oil, controlled with FGR [7] | 0.116 | 0.010 | 0.004 | 0.219 |
| **UGA Boiler No. 2 Emissions, Estimated at Max. Steam Load [2]:** | | | | |
| Chicken Fat, uncontrolled (w/o LNB or FGR) | 0.164 | not available | 0.000 | 0.000 |
| Yellow Grease, uncontrolled (w/o LNB or FGR) | 0.127 | not available | 0.012 | 0.000 |
| Choice White Grease, uncontrolled (w/o LNB or FGR) | 0.154 | not available | 0.014 | 0.000 |
| Tallow, uncontrolled (w/o LNB or FGR) | 0.118 | not available | 0.012 | 0.002 |
| No. 2 Fuel Oil, uncontrolled (w/o LNB or FGR) | 0.125 | not available | 0.003 | 0.150 |
| Chicken Fat, blended [6], uncontrolled | 0.137 | not available | 0.008 | 0.124 |
| Yellow Grease, blended [6], uncontrolled | 0.122 | not available | not available | 0.034 |
| Choice White Grease, blended [6], uncontrolled | 0.144 | not available | 0.012 | 0.119 |
| Tallow, blended [6], uncontrolled | 0.129 | not available | 0.008 | 0.102 |
| Chicken Fat, blended [6], controlled w. FGR [7] | 0.125 | not available | 0.014 | 0.138 |
| Yellow Grease, blended [6], controlled w. FGR [7] | 0.109 | not available | not available | 0.083 |
| Choice White Grease, blended [6], controlled w. FGR [7] | 0.138 | not available | 0.033 | 0.188 |
| Tallow, blended [6], controlled w. FGR [7] | 0.125 | not available | 0.008 | 0.119 |
| **US EPA Emission Factors for Criteria Pollutants (boilers > 100 MMBtu/hr heat input) [3, 4]:** | | | | |
| No. 2 Fuel Oil fired, controlled with FGR | 0.071 | 0.014 | 0.036 | 0.393 |
| Natural Gas fired, controlled with FGR | 0.098 | 0.002 | 0.082 | 0.000 |
| No. 2 Fuel Oil fired, uncontrolled (w/o LNB or FGR) | 0.171 | 0.014 | 0.036 | 0.393 |
| Natural Gas fired, uncontrolled (w/o LNB or FGR) | 0.186 | 0.002 | 0.082 | 0.000 |

1) Advanced Air Consultants, Murrayville, GA
2) Emissions data have been estimated using the test results from Advanced Air Consultants and ENERAC 3000E testing.
3) US EPA Fifth Edition 1995, with Supplements: A (1996), B ( 1996), D (1998), and E (1998)
4) The UGA No. 2 Boiler Operating Permit is based upon a 130 MMBtu/hr heat input.
5) SO2 emissions data have been reviewed in report Section 5.5, *Discussion.*
6) All blended fuels consist of 33% biofuel and 67% No. 2 fuel oil.
7) The FGR system was limited to 7% - 10% flue gas recirculation, see report Section 3.4.

Additional research is needed to understand:

1. What is the effect of biofuel/fuel oil blend proportions on viscosity and miscibility? What blend proportions maintain fluidity (low viscosity) over the range of ambient storage temperatures (say, 32 to 100° F.) typical in industrial applications? What is the minimum amount of agitation required?

2. What are minimum required specifications for fats and greases used as biofuel? What are the requirements for solids removal (screening), MIU (moisture, insolubles, unsaponifiables), Ultimate analysis (C, H, N, S), energy content, specific gravity, viscosity, etc.? How shall biofuels be specified for environmental permitting?

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